# Surface Bias Studies with Monte Carlo Models and Application to Jet-Hadron Correlations

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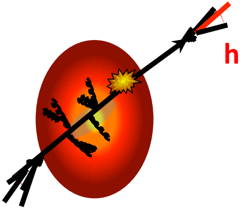
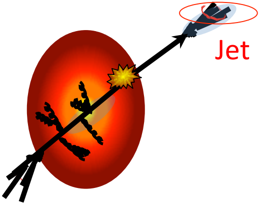
# Outline

1. Motivation
2. Models
3. Methods
4. Surface Bias Results
5. Observable effects

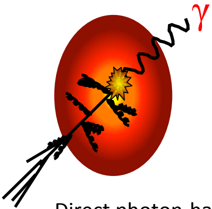
# Studying Energy Loss with Correlations




Hadron-hadron




Jet-hadron




Direct photon-hadron

-Surface bias by the trigger

-Broad parton energy distribution

-Less surface bias
-Several parameters to vary pathlength
-Better constrains initial parton energy

-No surface bias by trigger

-Photon $p_T$ approximates initial parton $p_T$

***Complementary observables***

# Why is Surface Bias Interesting

- Placing certain cuts on reconstructed jets may bias towards hard scatters occuring closer to the surface of the overlap region.
- For a dijet pair, this would enhances the path length of the "away-side" jet

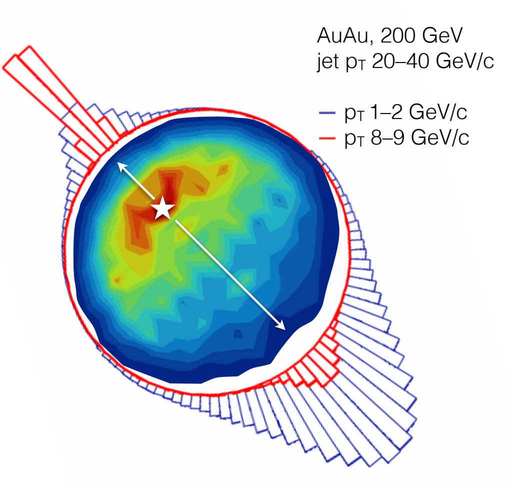



Figure: Biased hard scatter vertices and corresponding $\Delta\phi$ correlations

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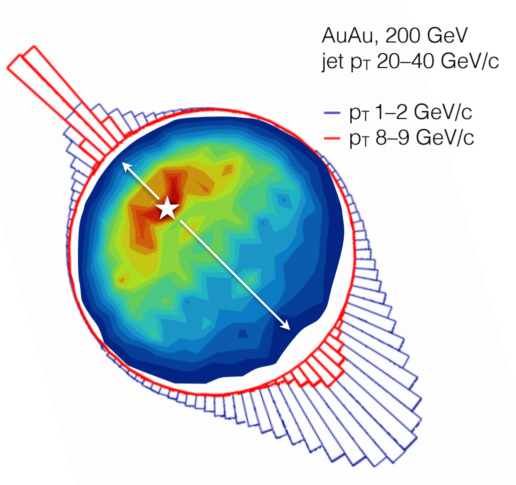


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- Is this consistent with models?
- Can we tune/control surface bias?

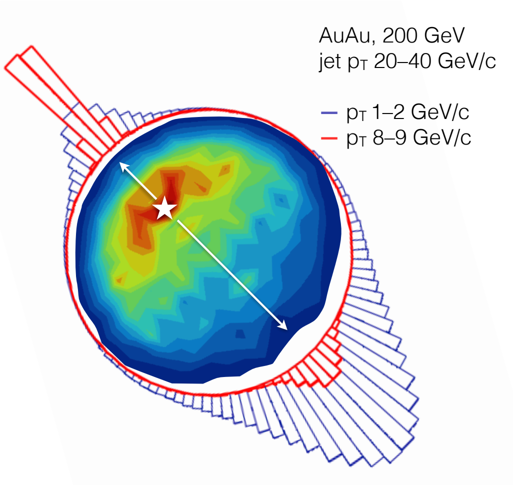



Figure: Biased hard scatter vertices and corresponding $\Delta\phi$ correlations

# Some Surface Bias Methods

- Reconstructing a jet
- Constituent Cut: cut on $p_T$ of tracks
- Hard Core Cut: Require jet to have $\geq 1$ high $p_T$ track

# Outline

# Models: JEWEL (Jet Evolution With Energy Loss)

K. Zapp et al. JHEP 1303 (2013) 080, EPJC C60 (2009) 617

- Explicit pQCD treatment of hard parton $2 \rightarrow 2$ scatterings with partons sampled from a simple (1+1D) hydro model
- Can keep or discard the medium partons that interact with partons from hard scatter
  - Keeping these "recoils" adds soft background

| Event type | Temperature (MeV) | $\sqrt{s}$ | Centrality |
|---|---|---|---|
| AuAu | 360 | 200 GeV | 0-5 % |
| PbPb | 500 | 2.76 TeV | 0-5 % |

# Models: YaJEM (Yet another Jet Energy-loss Model)

T. Renk, Phys. Rev. C 84 (2011) 067902 and refs therein

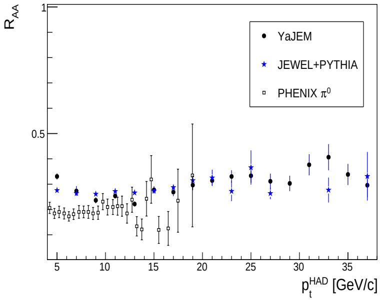
- Parton-medium interaction modelled via virtuality exchange:

$$\Delta Q^2 = \kappa \int \epsilon^{3/4}(\xi) d\xi$$

- Parton gains virtuality, leading to broadening and softening of shower. The YaJEM code does not generate events or simulate a medium.
- We input:
  - $\kappa$ parameter fit to charged hadron $R_{AA}$ at both energies: $\kappa = 2$
  - Hard Scatters from pythia
  - Energy density from JEWEL's hydro

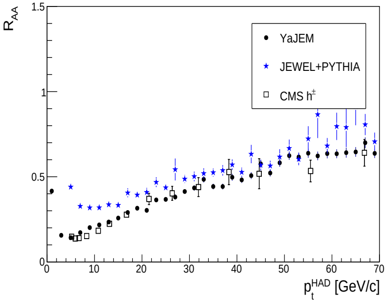
# Sanity Check

- Compare hadron $R_{AA}$
- Simulations consistent at high $p_T$




S. Adler et al. (PHENIX Collaboration) Phys. Rev. C 76, 034904

Figure: RHIC Comparison (200 GeV)




S. Chatrchyan eta l. (CMS Collaboration) Eur.Phys.J. C72 (2012) 1945

Figure: LHC Comparison (2.76 TeV)

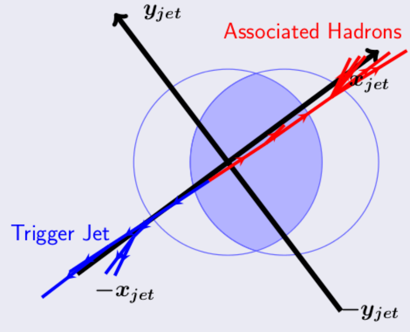
# Outline

# "Measurements" of Surface Bias

- Reconstruct leading jet using:

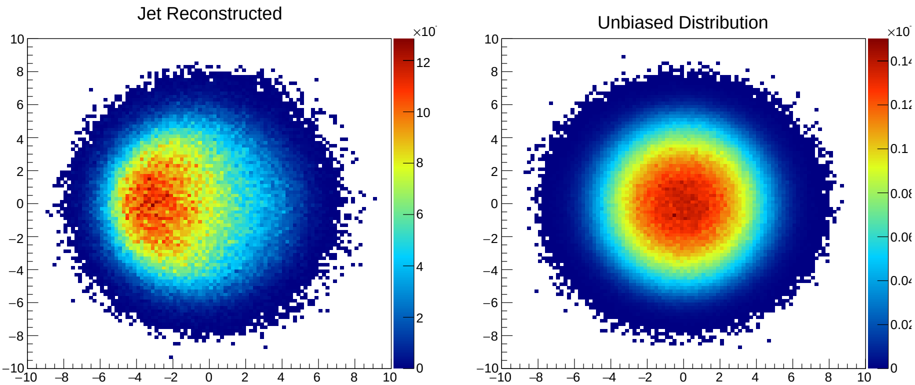
| Event type | Jet Algorithm |
|---|---|
| AuAu | Anti-kT (R = 0.4) |
| PbPb | Anti-kT (R = 0.2) |

  - $|\eta| < 1$ for all particles
  - $|\eta_{textjet}| < 1 - R$
- Define coordinates: $(x, y)_{jet}$, where $-x$ direction of jet
- Find distribution of hard scatter vertex



# "Measurements" of Surface Bias

Example Distributions: AuAu at $\sqrt{s} = 200$ GeV/c



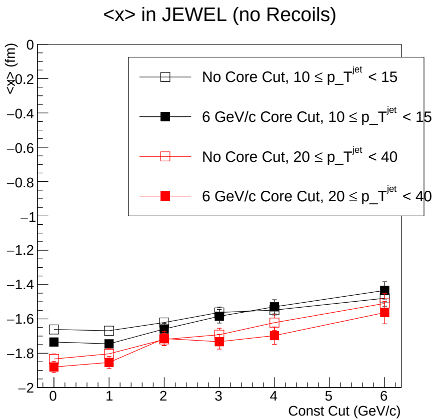

- Quantify bias by measuring average $x$ vertex of hard scatter in jet frame

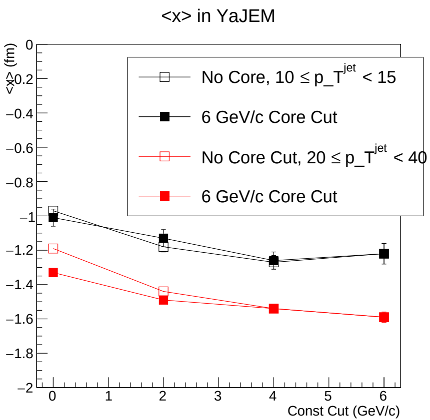
# Parameters We've Tested

- We test the following:
  - Requiring the trigger jet to have a "hard core" (constituent with $p_t > 6$ GeV/c)
  - Require constituents pass a $p_T$ cut before Jet Reconstruction
- We can also vary the level of the hard core cut (have done with JEWEL)

# Outline

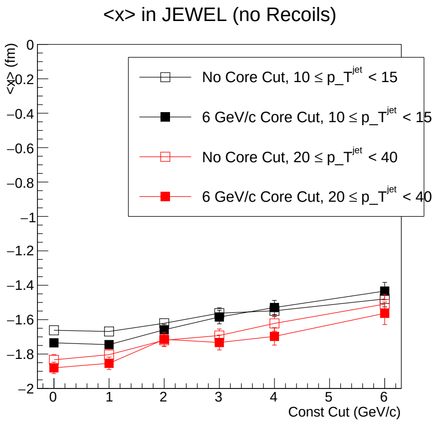
# Surface Bias results: AuAu at 200 GeV




- Models give same magnitude of bias
- Not very sensitive to changes in const. cut

# What about recoils in JEWEL? (AuAu at 200 GeV




- JEWEL yields less YaJEM-like results without recoils.
- May improve with proper subtraction of JEWEL's recoil 'background'

# Surface Bias results: PbPb at 2.76 TeV

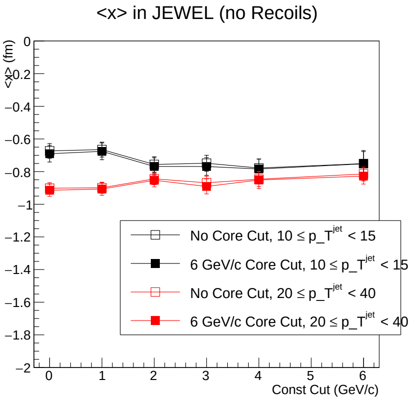



Figure: JEWEL

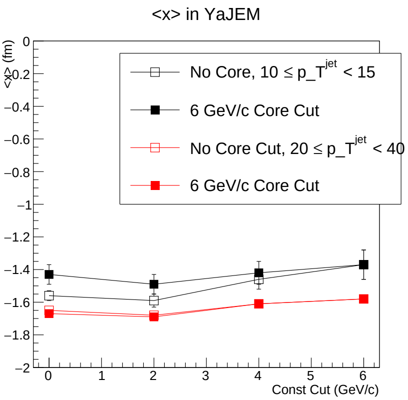



Figure: YaJEM

- Hard core effect still not signficant in $< x >$
- JEWEL shows less bias at LHC energy, but YaJEM does not. Why?

# Surface Bias Results: Strange YaJEM surface bias at LHC, (2.76 TeV)

Recall that we are using $R = 0.4$ for RHIC energies and $R = 0.2$ for LHC energies. We have begun investigating effect of $R$.

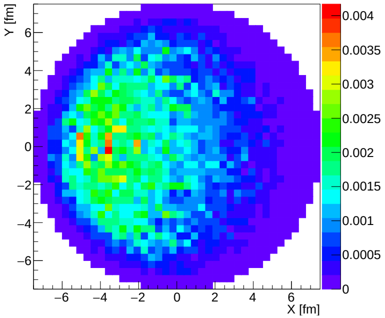



Figure: anti-kt, R = 0.4

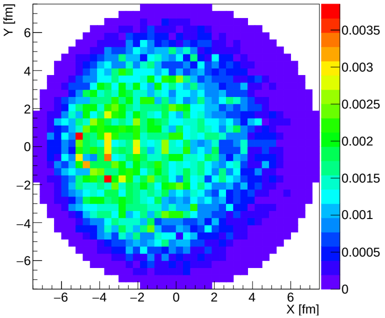
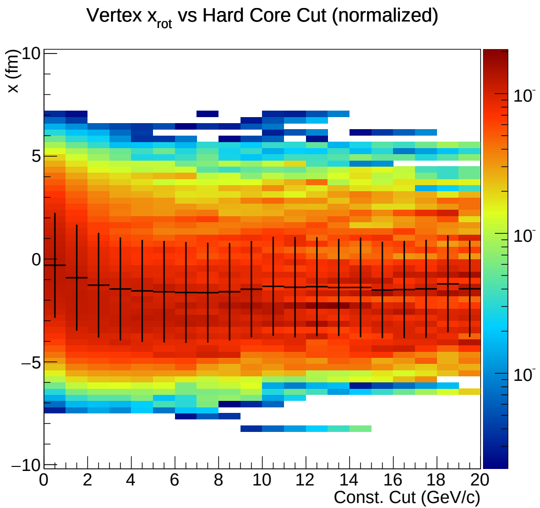



Figure: anti-kt, R = 0.6

- Sensitivity present, but doesn't explain JEWEL-YaJEM difference

# Surface Bias Results: Hard Core cut vs $x$, AuAu at 200 GeV (JEWEL, No Recoils)




- Each column is the $x$ vertex distribution of hard scatters.
- Profile plotted showing mean $x$, standard deviation

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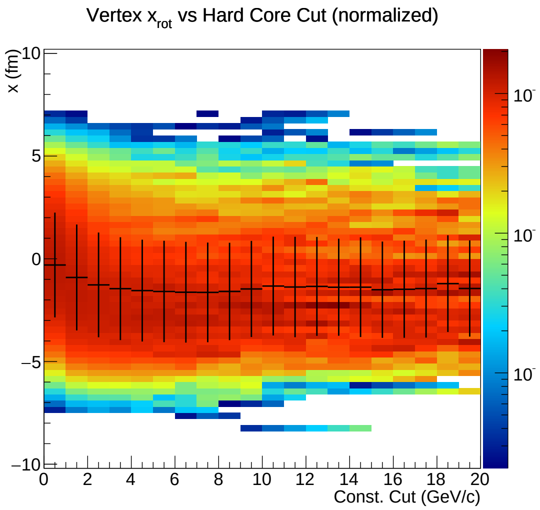


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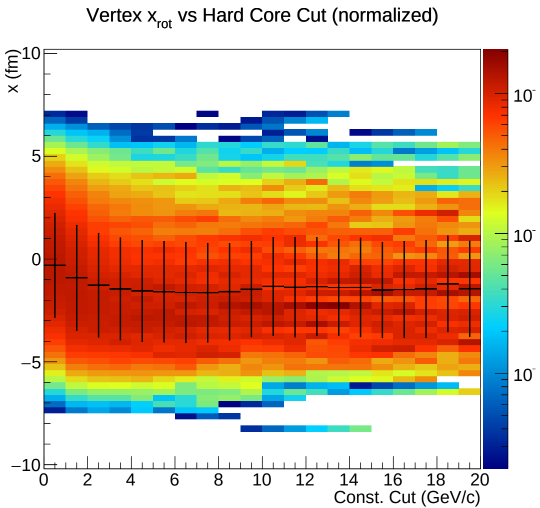



- Each column is the $x$ vertex distribution of hard scatters.
- Profile plotted showing mean $x$, standard deviation
- Note: these are inclusive jets, no constituent cut
- Hard Core cut effective around 4-8 GeV/c

# Surface Bias Results: Hard Core cut, RHIC vs LHC (JEWEL)

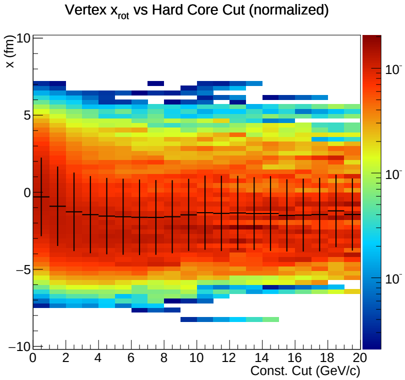



Figure: AuAu (200 GeV) (JEWEL, No recoils)

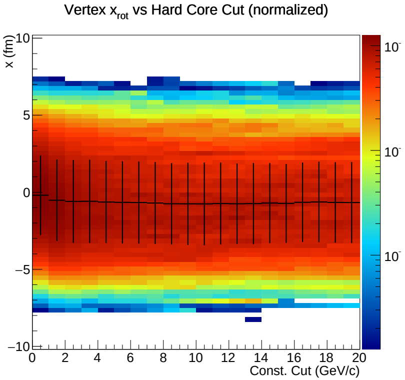


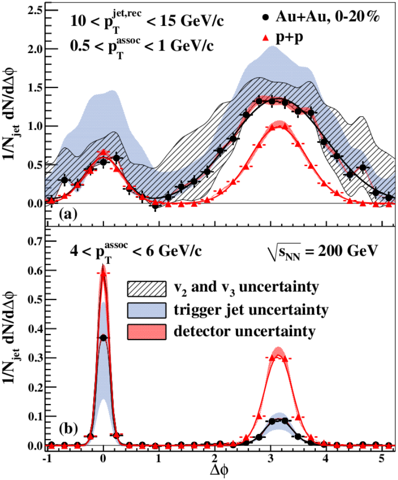

Figure: PbPb (2760 GeV) (JEWEL, No recoils)

- Demonstration of relative difficulty of surface bias at the LHC

# Outline

# Observable Effects: Jet-Hadron Correlations

- Trigger on high $p_T$ jet, correlate hadrons (or tracks)
- Subtract combinatorial background (fake jets), if necessary
- This has been studied at RHIC by STAR (arxiv:1302.6184) and at the LHC by CMS (arXiv:1601.00079)
- We follow the STAR study by look at awayside peak in angular correlations




Phys.Rev.Lett. 112 (2014) 12, 122301

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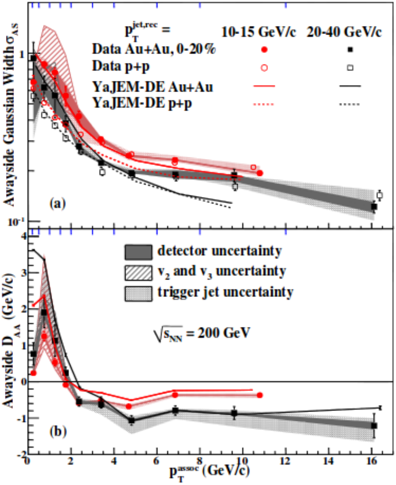


Phys.Rev.Lett. 112 (2014) 12, 122301

- Fit awayside to $Y_{AS} * \frac{1}{\sqrt{2\pi\sigma_{AS}^2}} \exp -(\Delta\phi - \pi))^2/2\sigma_{AS}^2$
- Compare $\sigma_{AS}$ in AA to pp
- Calculate $D_{AA}(p_T^{assoc}) = Y_{AS}^{AA} * \langle p_T^{assoc} \rangle - Y_{AS}^{pp} * \langle p_T^{assoc} \rangle$

# Observable Effects: Jet-Hadron Correlations

What we do:

- Fit to a sum of two gaussians for near side, and a generalized normal distribution for the awayside
  - 2 Gaussians for near side peak (shape affected by jet reconstruction)
  - Generalized normal dist. fits awayside peak better than Gaussian
- We use Full Width at Half Maximum (FWHM) to characterize width

# Example Widths Comparison: pp vs AuAu at 200 GeV

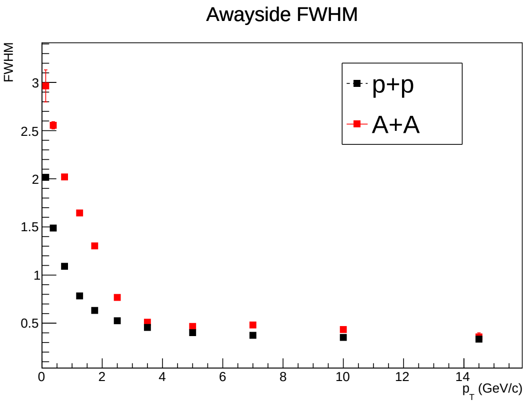


Figure: FWHM for $15 \leq p_T^{jet} < 20$ (JEWEL, with RECOILS)

- Example of what a width comparison can look like
- Model prediction for broadening of awayside peak for low associated $p_T$

# Effect on Jet-hadron correlations: Widths

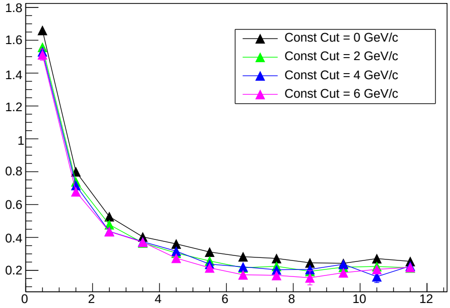


Figure: FWHM for AuAu at 200 GeV, YaJEM, $20 \leq p_T^{jet} < 40$

Now look width prediction with different constituent cuts

- With higher surface bias, the awayside width appears narrower
- Apparent narrowing of awayside peak with more surface bias?

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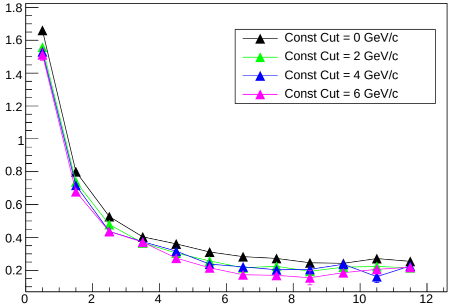


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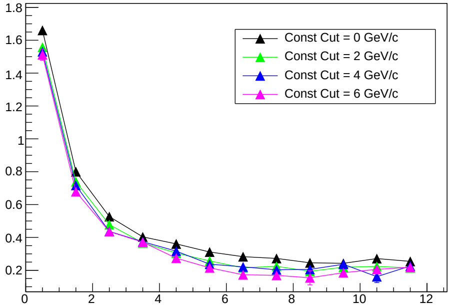


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- Apparent narrowing of awayside peak with more surface bias?
- A sign of collimation in the model? ...
- Or a result of changing jet energy scale and quark/gluon ratio?

# Other effects: Leading Jet $R_{AA}$

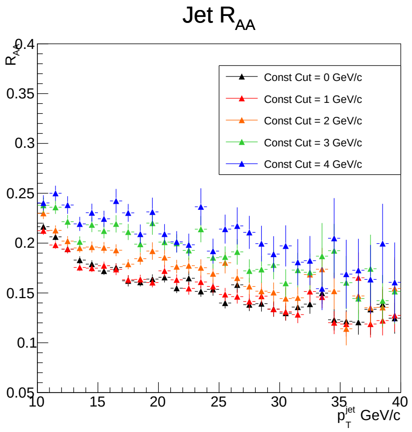


Figure: Leading Jet $R_{AA}$ for AuAu at 200 GeV (JEWEL, No recoils)

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  - Consistent with surface bias, but ...

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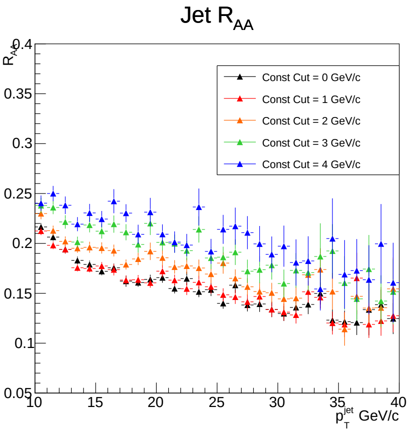


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- Higher Const Cut $\implies$ less supression?
  - Consistent with surface bias, but ...
  - Like the widths, this could also be explained by selecting quark jets, or by changing jet energy scale

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- The hard core cut does not have a significant effect beyond reconstructing jets (in these models)
- Varying the consitituent cut does not give us a powerful way to tune surface bias
- Need to investigate:
  - Surface bias in bins of true hard scatter and of background subtracted $p_T$
  - Effect of jet algorithm
  - Hadron Trigger
  - Effect of more advanced hydro
  - Effect on quark/gluon selection

# Backup Slides

# Strange YaJEM surface bias at LHC

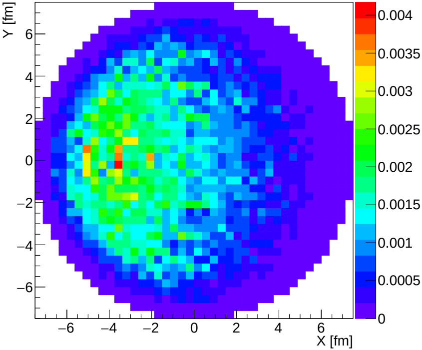


Figure: anti-kt, R = 0.4

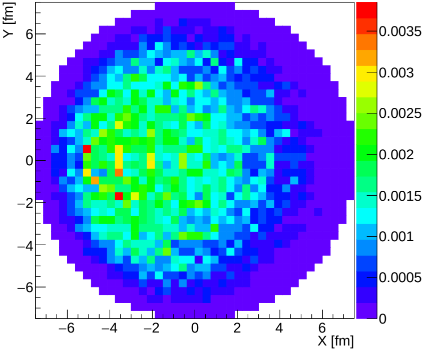


Figure: anti-kt, R = 0.6

- Surface bias is also sensitive to R

# Strange YaJEM surface bias at LHC

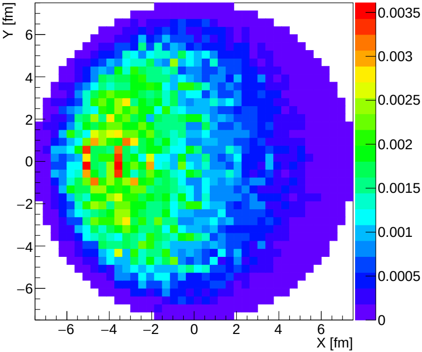


Figure: 1+1D Hydro (from JEWEL)

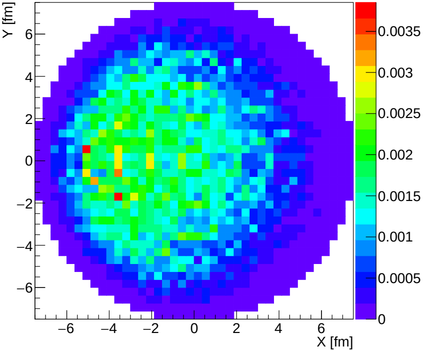


Figure: 2+1D Hydro (superSONIC, initial conditions from Glauber built into JEWEL)

- Noticeable difference between hydro models

# Parameters

| Event type | Temperature (MeV) | $\sqrt{s}$ | Centrality | Recoils? |
|---|---|---|---|---|
| AuAu | 360 | 200 GeV | 0-5 % | Keep |
| PbPb | 500 | 2.76 TeV | 0-5 % | Keep |

Table: JEWEL Parameters

| | |
|---|---|
| $\kappa$ | 2 |
| Hydro | Same as JEWEL |

Table: YaJEM parameters

| Event type | Jet Algorithm |
|---|---|
| AuAu | Anti-kT (R = 0.4) |
| PbPb | Anti-kT (R = 0.2) |

Table: Analysis Parameters

# Background subtraction for JEWEL

- Necessary when recoils in JEWEL are kept. Results in many low pt particles, not unlike an actual underlying event.
- Multiple techniques tried
- Currently: fit nearside of $\Delta\phi - \Delta\eta$ correlations to sum of two Gaussian + 'tent' function
  - $\eta$-depedence $\implies$ not enough, may need to use mixed event method

# Widths Method Explanation

- Generalized Normal distribution in terms of *omega* (FWHM):
  - $f_{\mu,\omega,\beta}(x) = \frac{\beta(\ln(2))^{1/\beta}}{\omega\Gamma(1/\beta)} \exp\left\{-\ln(2)(2|x-\mu|/\omega)^{\beta}\right\}$
- Trying new definition for width: full width at half max
  - For Gaussian: $\omega = 2\sigma\sqrt{2\ln(2)}$
  - For Generalized Normal: $\omega = 2\sigma\sqrt{\frac{\Gamma(1/\beta)}{\Gamma(3/\beta)}}(\ln(2))^{1/\beta}$
- Reparameterized:
  - $f_{\mu,\omega,\beta}(x) = \frac{\beta(\ln(2))^{1/\beta}}{\omega\Gamma(1/\beta)} \exp\left\{-\ln(2)(2|x-\mu|/\omega)^{\beta}\right\}$

# Example Width Method Comparisons

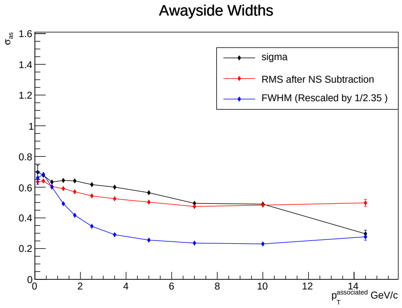


Figure: pp @ 2.76 TeV,
10 GeV/c $< p_T^{jet} <$ 15 GeV/c

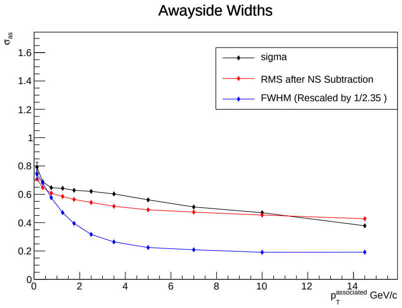


Figure: pp @ 2.76 TeV,
15 GeV/c $< p_T^{jet} <$ 20 GeV/c

- $S \equiv \frac{N_{\text{vertices}}(x<0)}{N_{\text{vertices}}(x>0)}$

# Surface Bias results: AuAu at 200 GeV

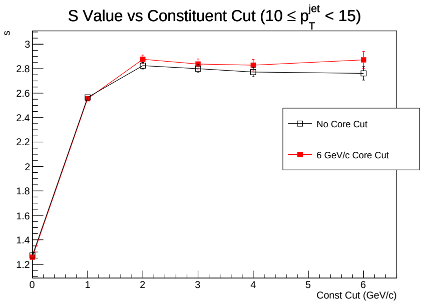


Figure: JEWEL

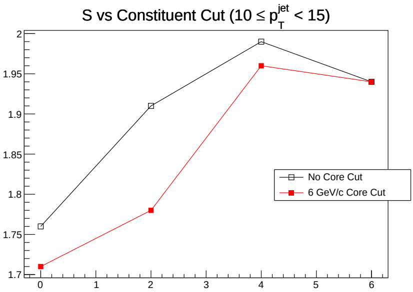


Figure: YaJEM

- Higher $S \implies$ more surface bias

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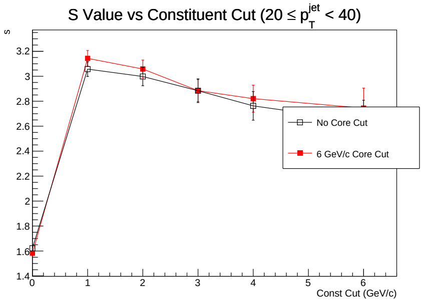


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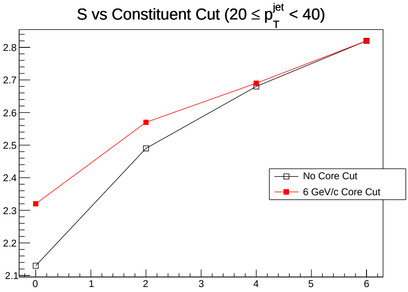


Figure: YaJEM

# Surface Bias results: PbPb at 2.76 TeV

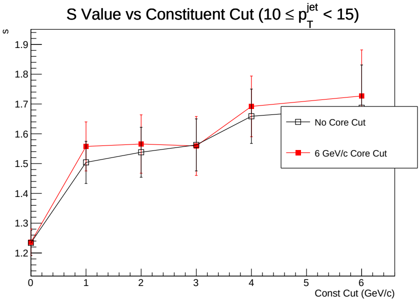


Figure: JEWEL

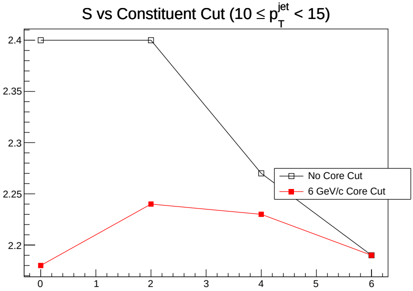


Figure: YaJEM

- Higher $S \implies$ more surface bias

# Surface Bias results: PbPb at 2.76 TeV

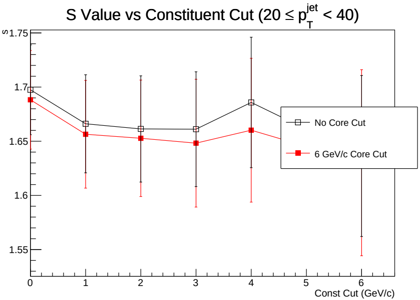


Figure: JEWEL

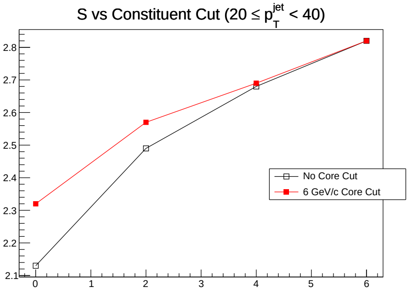


Figure: YaJEM

# Jet-Hadron Observables

- Trigger on high $p_T$ jet, correlate hadrons in $\Delta\eta, \Delta\phi$
- Subtract combinatorial background (fake jets), if necessary

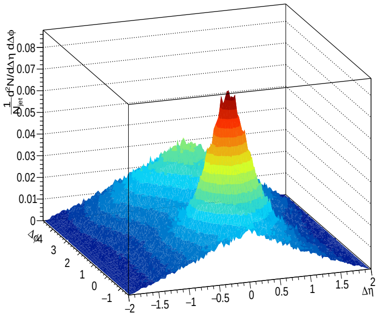


Figure: $\Delta\phi - \Delta\eta$ Correlations

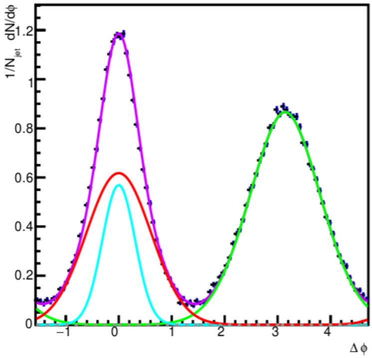


Figure: $\Delta\phi$ Projection

# Example of Nearside Shape

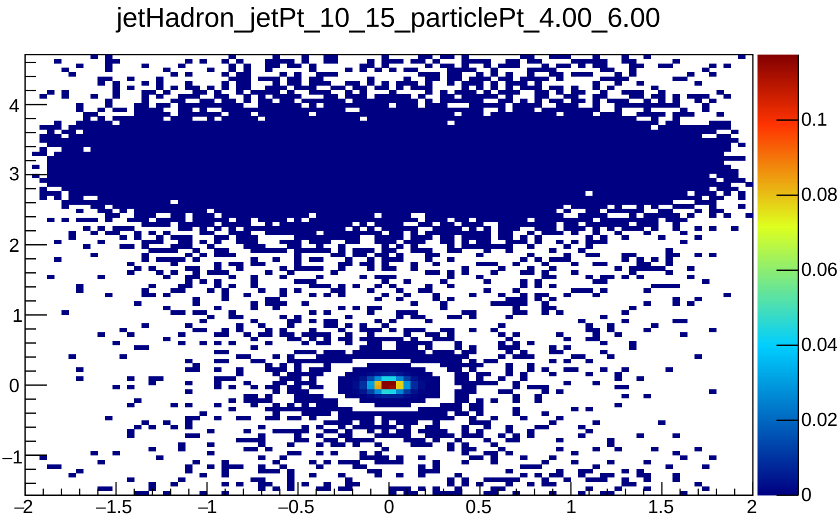


Figure: AuAu, CCUT = 2 GeV/c, no Hard Core

# Effect on Jet-hadron correlations: Widths (JEWEL)

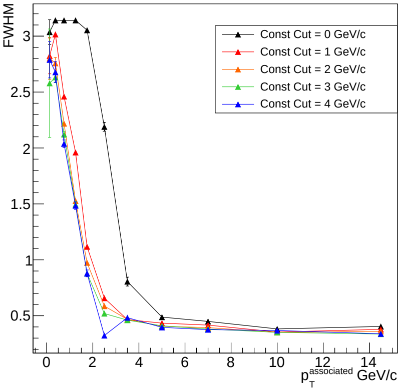


Figure: FWHM for AuAu at 200 GeV, JEWEL, $20 \leq p_T^{jet} < 40$

# Effect on Jet-hadron correlations: Widths (JEWEL)

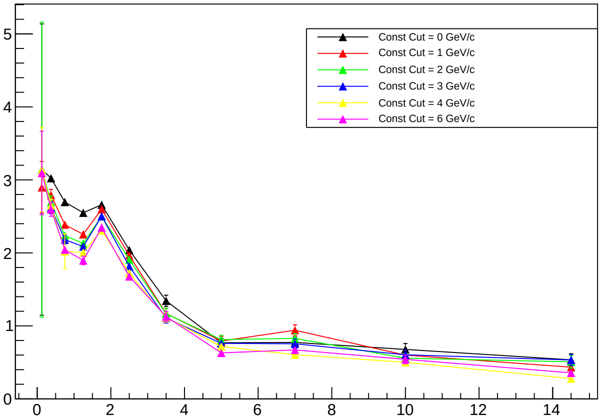


Figure: FWHM for PbPb 2.76 TeV, JEWEL, $20 \leq p_T^{jet} < 40$